FORECASTING MARINE FOG ON THE WEST COAST OF THE UNITED STATES USING A LINEAR DISCRIMINANT ANALYSIS APPROACH

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

FORECASTING MARINE FOG ON THE WEST COAST OF THE UNITED STATES USING A LINEAR DISCRIMINANT ANALYSIS APPROACH

by

Michael Charles McConnell, Sr.

September 1975

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Forecasting Marine Fog on the West Coast of the United States Using a Linear Discriminant Analysis Approach

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The objective of this study is to develop classification equations to forecast the daily probability of occurrence of marine fog at selected locations on the west coast of the United States, using parameters easily obtainable from upper-air soundings and surface observations. In order to achieve this objective a computerized stepwise linear discriminant analysis program is extensively employed. Data input consists of surface and radiosonde observations for the five-year period 1 July 1968 to 30 June 1973 at three U. S. west coast stations, namely San Diego and Oakland, California and Quillayute, Washington.

Tables showing the number of fog and no-fog cases, the classification functions, and the percentages of correct fog and no-fog discrimination are presented for each station. The most capable fog/no-fog discrimination parameters are discussed for each set of classification equations. Test results for the San Diego equations using a three-year independent data set are also shown.

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I. INTRODUCTION

Marine fog is an impediment to both commercial and military shipping and air operations. Such fog has often caused costly delays to commercial ship owners and domestic air carriers while endangering lives and property as a result of low visibilities. Naval operations such as aircraft transfer and landing, antisubmarine warfare and amphibious maneuvers, navigational reconnaissance and search and rescue missions may be hampered by marine fog. The importance and impact of marine fog on naval operations during World War II and the recent costs (1969-1974) in lives and property damage of ship and aircraft accidents suffered by the United States Navy during fog situations has been described by Wheeler (1974).

Recognized as an important meteorological problem, marine fog prediction and dissipation have been the subjects of ongoing research by several Department of Defense (DOD) activities. In particular the Naval Air Systems Command (NAVAIR) and the Office of Naval Research (ONR) have jointly sponsored marine fog research in an attempt to model and simulate the fog for purposes of prediction. A Naval Postgradute School (NPS) group, under the direction of Dr. Leipper, Chairman of the Department of Oceanography, and Dr. Renard of the Department of Meteorology, is participating in this coordinated effort with the following specific objectives:

"1. To observe and describe the formation and dissipation of fog at sea in cooperation with Cornell Aeronautical Laboratory, Inc.

2. To relate the synoptic variables in meteorology and oceanography which are important in marine fog formation and dissipation to microphysical and micrometeorological characteristics.

3. To improve marine fog forecasting and to develop marine fog prediction methods."[1]

Several recent NPS studies have addressed the problem of marine fog climatology of the North Pacific Ocean and incorporated a method of synthesizing ships' surface synoptic reports for the purpose of deriving frequencies of marine fog occurrence (Englebretson, 1974; Daughenbaugh, 1975; Renard, Englebretson and Daughenbaugh, 1975; Willms, 1975). Wallace (1975) and Hale (1975) have explored the feasibility of using meteorological satellite data as a means of discerning the presence of marine fog. In a study by McClure (1974), a potential link between temperature inversions and the occurrence of marine advection fog was investigated, in order that temperature inversion parameters could possibly be used as forecasting aids at coastal stations.

Although the Environmental Prediction Research Facility (EPRF), Monterey, California, is engaged in numerical

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[1]Leipper, D. F., and others, 1973: Observation, Analysis and Prediction of Marine Fog. Naval Postgraduate School, Department of Oceanography Annual Report for period 1 July 1972 to 30 June 1973, p. 10.

modeling studies on the physics of fog formation, maintenance and dissipation (Feit, 1972; Barker, 1973), and researchers elsewhere, such as Mack et al (1973), have developed numerical models of advection fog, few operational forecasting schemes for marine fog on the west coast of the United States have been developed to date. Fleet Numerical Weather Central (FNWC), Monterey, California, has an operational advection fog program ("FTER") which forecasts grid point fog probabilities to 48 hours based on a system of multi-parameter tests (U. S. Naval Weather Service Command, 1975). Given the correct humidity values, this program gives acceptable results in cases of broad-scale fog. However, its primary weakness stems from the large 63x63 grid -- local effects just cannot be reconciled.

"Forecasting fog is one of meteorology's hardest problems. This is because there are so many factors involved--moisture, temperature, wind, geography, stability, cloud cover, and several more."[2] It is hoped that this study may provide insight and methodology which will aid forecasters in predicting the occurrence of marine fog for selected locations on the west coast of the United States.

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[2]U. S. Naval Weather Service Command, 1975: U. S. Naval Weather Service Numerical Environmental Products Manual, NAVAIR __________, Department of the Navy, Washington, D. C., p. 4.26-2.

II. BACKGROUND

A. A REVIEW OF SELECTED PREVIOUS FOG RESEARCH

A considerable amount of research into the problem of marine fog on the North American west coast has been conducted in the southern California area. In 1948 Leipper (1948) devised a model to illustrate the manner in which fog situations develop in the San Diego area. This model was described in four stages and is still used to some degree by military forecasters in the southern California area.

The first stage or initial conditions in Leipper's model requires the presence of air over the sea which has a temperature higher than the sea-surface temperature and which is relatively dry aloft. This condition guarantees the formation of an inversion which will restrict the vertical movement of moisture and thus cause a thin lower layer of air to approach saturation. Such initial conditions are typically brought about when a lobe of the North Pacific subtropical anticyclone pushes inland over northern California causing a general easterly flow over southern California so that the air arriving at San Diego is warm and dry, having descended the 4000-foot slope of the coastal mountains.

In the second stage of fog development, the easterly flow weakens, the flow of warm subsiding air toward the sea

decreases, and the air offshore from San Diego remains in a relatively stagnant condition. Due to evaporation from the sea the moisture content of the lower layers increases considerably, and the heat content decreases due to the conduction of heat downward. During this process a surface inversion is formed and the lowest air layers become nearly saturated at a temperature close to that of the underlying sea surface.

Fog forms in the third stage as the normal northwesterly airflow and sea breeze regime returns. The fog is created in the thin surface layer at sea as the warm, nearly saturated air moves over the colder coastal waters. Thus, fog is produced by cooling from below (Leipper, 1968). Once the white cloud is formed, incoming radiation reflected from the top and heat radiated from the cloud itself results in cooling of the thin fog layer to a temperature lower than the ocean surface in the vicinity. Then as the sea breeze strengthens during the daytime, the fog is advected shoreward.

The fourth and final stage is characterized by the deepening of the nearly adiabatic lower layer to approximately 400 feet or more. Since evaporation from the sea continues and the presence of the strong inversion still restricts the vertical movement of moisture, the dew point remains high in the marine layer. After the daytime sea breeze carries the fog over the shore, radiation and conduction of heat from the land mass dissipate the fog somewhat, but the nearly

adiabatic layer, being deeper than the previous stage, is not destroyed as rapidly. Rather, it retains its high moisture content in vapor form and moves inland. As the marine layer beneath the inversion continues to deepen, a point is reached where the mixing and cooling processes do not result in condensation throughout the layer. Then the upper portion fills with water particles first and fog does not form on the ground. In this way the fog sequence is ended and the stratus regime begins. The complete fog sequence Leipper described usually extends over a period of about five days.

In a later work Leipper (1968) compared the meteorological conditions associated with the observance of a sharp smog bank near Riverside, California with those previously shown to be related to winter fogs in southern California. He believed that the characteristics of certain stages of these fog situations in winter were quite similar to those observed by Edinger (1963) in July 1961 and to those reported by Stephens (1965). The distinguishing characteristic was the presence of unusually warm, dry air over the inversion and a very cold marine layer beneath it. In such situations the air above the inversion is often nearly 10 C warmer than the underlying sea. The combination of very warm air aloft and an unusually cold marine layer results in the strongly stable situation described by both Edinger and Stephens as having high smog potential when it moves inland. Such situations in the San Diego area were associated with fogs having sharp boundaries.

Three nondiurnal indices presented by Leipper in 1948, and found useful in the prediction of west coast fog, also may be important in predicting situations favorable to the shallow sharp-banked smogs which are often observed. The indices are composed from data obtained in the morning radiosondes used together with the coastal water temperature and the surface dew point in the marine layer. Leipper (1948) described the indices as follows:

1. Height of the Inversion Base: The height above which the air temperature increases with height at the most rapid rate on the morning raob (radiosonde observation).
2. Temperature Index: The quantity (Ta-Tw); if an inversion exists with base below 3,000 feet, Ta is the highest air temperature above the inversion base on the morning raob, otherwise Ta is the surface air temperature, and Tw is the coastal sea-surface temperature.
3. Moisture Index: The difference between the afternoon dew-point and the coastal water temperatures.

The conditions found most favorable for fog occurrence, if applicable to smog, require the base of the inversion to be below 1,300 feet, the temperature index to be positive, and the moisture index to be greater than -5 C.

Schroeder et al (1967) describe three significant aspects of marine air invasion along the west coast of the United States, two of which are related to fog development. The

most noticeable invasion is that of the diurnal sea breeze. This well known phenomenon is produced by differential heating of the land and water masses and results in the sea breeze circulation cell which brings cool, moist marine air landward. One of the most distinctive characteristics of the sea breeze is the front-like appearance at its leading edge.

The inland movement of the sea breeze and its front is strongly controlled by terrain features. In addition, the large-scale weather patterns affect the sea breeze. When the synoptic-scale gradient flow is directed offshore, the sea-breeze front is intense but does not penetrate far inland, and the strength of the flow is weak. However, when the gradient flow is onshore, the front is weak and the sea-breeze flow is strong, resulting in considerable inland penetration.

Perhaps the most significant marine air invasion is that of the United States west coast monsoon. This phenomenon begins in the late spring and continues until fall, bringing a slow, steady transport of marine air inland from the North Pacific Ocean high pressure cell. This subtropical high is composed of a shallow marine layer capped by a subsidence inversion. The marine inversion is the most pronounced and shallow during the monsoon season. Irregular fluctuations in the marine inversion are generally related to the synoptic weather patterns, while the diurnal variations of the inversion depth are partly related to the interaction of the sea breeze and the monsoon. The monsoon is generally confined to

a layer less than 2 km deep and its inland path is primarily through low gaps in the coastal mountains.

In summary, the monsoon is a feature of the general atmospheric circulation which undergoes modification at the coastline, interacts with both the sea breeze and the moving synoptic-scale systems, and is confined to a very shallow layer.

One of the most comprehensive studies of marine-fog forecasting on the west coast was done at Scripps Institution of Oceanography during a contract with ONR, and was supervised by D. F. Leipper (Leipper and others, 1948). The purpose of this "Fog Project" was to develop and to test principles which might serve as a basis for fog forecasting in coastal areas and possibly elsewhere.

The "Final Report of the Fog Project" outlines some of the theory of condensation and evaporation which have particular importance in the development and application of the fog forecasting technique. It is generally believed that the local fog forecasting problem is primarily one of predicting the moisture content of the air and the amount of local cooling which will occur. The sea-surface temperature is an important variable in determining the amount of modification (measured by the change in content of heat and moisture) which will be brought about in a given overlying air mass. This temperature is also a convenient quantity with which other more erratic quantities such as air temperature and dew point may be compared, as was done in Leipper's (1948) non-diurnal fog indices. In low coastal regions the

dew-point temperature is a reliable index of moisture content, and is the most convenient quantity for use in forecasting changes in moisture which will affect fog formation.

The forecasting procedure devised by the researchers of the "Fog Project" consists of three parts. First the forecaster must prepare prognostic charts in order to determine from them certain fundamental weather features (local features such as wind speed, cloud cover, range of ceiling and surface pressure; also, synoptic-scale features such as changes in surface air flow and subsidence). The second step involves applying statistical aids (e.g., climatological data, temperature and time forecasts, and visibility data) to determine the local changes in heat and moisture content of the air associated with the fundamental features which are forecast. Finally, the forecaster must determine the visibility from the moisture content, changes in heat content and other available data by applying empirical rules.

Information obtained from radiosondes such as the height of the inversion base, the strength and thickness of the inversion, etc., may be significant in fog forecasting. In the "Final Project" J. B. Wickham discusses why the inversion index (height of the inversion base) is important. Generally speaking, when a strong temperature inversion exists over a nearly adiabatic layer, the moisture flux through the inversion is small as compared with the flux through the surface layer. Consequently, moisture is trapped below the inversion and over a period of time, near saturation of the entire adiabatic layer can occur. Not only does near saturation

occur most rapidly with low inversions, but the amount of cooling necessary to produce condensation throughout the layer is less for thin layers than for thick ones. Thus, the time required to approach saturation and the amount of cooling needed to form fog are both functions of the height of the inversion base. The inversion index is of further importance since it effects the diurnal temperature range and indicates the location of the dry marine-air boundary.

A more recent investigation into the relationships between temperature inversions and the occurrence of marine advection fog was undertaken by McClure (1974). He studied three primary inversion parameters: the height of the inversion base, thickness of the inversion layer, and the temperature gradient within the inversion layer, using ten months of surface and upper-air data (July 1973 to April 1974). The upper-air sounding stations used were San Diego (Montgomery Field), California; Oakland (International Airport), California; and Quillayute, Washington. The surface observation stations were San Diego (Lindberg Field), California; Oakland (International Airport), California; and Seattle-Tacoma (International Airport), Washington.

Because of the considerable geographic separation (nearly 100 miles) between the upper-air soundings taken at Quillayute and the surface fog observed at the Seattle-Tacoma Airport, no definitive relationships were achieved. However, at San Diego a relationship between the change in inversion parameters and the occurrence of fog was found to exist in

both the summer and winter seasons. At Oakland, consistency in the change of one parameter was shown for most of the data period.

A brief summary of some of McClure's relationships between temperature inversions and marine advection fog follows.

1. Summer fog cases are generally preceded by an inversion in the atmosphere below 850 mb. For soundings taken during fog, the lack of an inversion below 850 mb is the exception rather than the rule, especially during the summer and early fall.
2. Most fall and winter fog cases (80%-90%) are preceded by an inversion.
3. During the summer season in San Diego the thickness of the 0000 Greenwich Mean Time (GMT) inversion layer usually decreases within 24 hours prior to the occurrence of fog and the inversion base lowers. Cooling of the surface layer precedes the fog. Where fog persists there is a general warming trend in the lower atmosphere associated with a subsidence inversion in the 0000 GMT sounding.
4. During the winter season in San Diego the inversion base rises in the last 24-hour change of the 0000 GMT sounding before a fog sequence. In the 1200 GMT sounding the inversion is based at the surface for at least four soundings prior to the fog. Within 24 hours of the commencement of fog, the strength of the inversion layer lessens, the depth increases, while the temperature gradient decreases.

5. In Oakland's summer season there is a decrease in the inversion thickness and an increase in the temperature gradient in the 0000 GMT sounding within 24 hours prior to the fog occurrence.

6. In Oakland's fall season there is almost always a surface inversion in the last two 1200 GMT soundings prior to the onset of fog. This is also true for the winter months of January and February.

7. During the winter season in Oakland inversions do not always accompany or precede fog. If an inversion exists, it is usually weakening prior to fog occurrence, while the inversion thickness and temperature gradient are decreasing.

McClure's investigations and recommendations served as the platform from which this study was launched. A much broader data base and computer analysis was believed to be essential if more concrete relationships were to be made. Additional parameters were needed, especially within the surface observations. Finally, it was considered to be highly desirable to have the upper-air sounding station and the surface observation station at the same location. These changes and others, plus a different analysis approach, were incorporated in this research.

III. OBJECTIVE, DATA AND DEFINITIONS

A. OBJECTIVE AND APPROACH

The objective of this study was to develop classification equations to forecast the daily probability of occurrence of marine fog at selected locations on the west coast of the United States, using parameters easily obtainable from upper-air soundings and surface observations. In order to achieve this objective, a stepwise linear discriminant analysis program, BMD07M (Dixon, 1973), and the IBM 360 computer were extensively employed. Application of these powerful computational resources to the available data would hopefully statistically reveal what parameters are most significant in marine-fog prediction.

B. DATA DESCRIPTION

Upper-air soundings and surface 3-hourly airways reports for the five-year period of 1 July 1968 to 30 June 1973 were used for three U. S. west coast stations: San Diego, California; Oakland, California; and Quillayute, Washington. This initial data base included almost 11,000 soundings (two daily) and over 43,700 surface reports (eight daily). Sea-surface temperature information for the period of interest was extracted from the Fishing Information Bulletin Supplements published by the U. S. Department of Commerce. The data provided by the Naval Weather Service Detachment,

Asheville, North Carolina were taken from the National Climatic Center's historical data files, known as Tape Data Family-14 and -56 (TDF-14 and TDF-56), Airways Surface Observations, and Radiosonde Data.

C. DEFINITION OF FOG AND FOG DAY

For purposes of this study "fog" (as in marine advection fog) is defined as a visible aggregate of minute particles of water (droplets) based at the earth's surface, which reduces horizontal visibility to less than seven miles and is an obstruction to vision at the reporting station. A "fog day" as used in this study was defined as the period from 1601 PST on one calendar day through 1600 PST on the following calendar day, so that a day would usually include both the formation and dissipation time of fog (after Leipper, 1948).

IV. EXPERIMENTAL PROCEDURES

A. DATA PREPARATION AND ORGANIZATION

In any study involving large amounts of information perhaps the most difficult and crucial first step is the proper preparation and organization of the data. Initially the data tapes had to be screened for missing reports and modified for the use of FORTRAN programming on the NPS IBM 360 computer. All surface and upper-air reports were identified by year, month, day and hour numeric time groups. The upper-air sounding time group identifiers were converted from Greenwich Mean Time (GMT) to Pacific Standard Time (PST) in order to conform with the airways surface observation time groups. The sea-surface temperature (SST) data were extracted twice a month (1st to the 15th and 16th to the 30th/31st) from the SST charts in the Fishing Information Bulletin Supplements (U. S. Department of Commerce, 1968-1973), and were added to the surface report data. The temperature information on the surface reports was then converted from the Fahrenheit scale to the Celsius scale, thereby utilizing the metric system for all data fields.

Each 3-hourly surface observation contains 35 data fields (not including the tape and station number and the date), which describe the following meteorological parameters: ceiling, visibility, wind direction and speed, dry-bulb

temperature, wet-bulb temperature, dew-point temperature, relative humidity, sea-level pressure, station pressure, sky condition, cloud information (amount, type, and height of as many as four cloud layers plus the total amount and total opaque amount, as well as summation amounts at the second and third layers), and other atmospheric phenomena, including wind storms, liquid and frozen precipitation, and obstructions to vision. This last data field is especially important since the definition of a fog occurrence is based upon the presence of fog at the station as an <u>obstruction to vision</u>. Furthermore, the code lists three types of fog: "fog", "ice fog", and "ground fog". Although marine advection fog is not explicitly indicated, the great majority of fog occurrences were described as "fog" and are probably marine fogs considering the three stations selected for this study.

The upper-air soundings were reported twice daily (0400 and 1600 PST) and contained the following data for both mandatory and significant levels: pressure in millibars (mb), height in meters (m), temperature in degrees Celsius, relative humidity, and wind direction and speed. Since fog is a surface phenomenon, the entire sounding was not needed. As reported by McClure (1974), the important inversion information relating to the occurrence of fog existed at 850 mb and below. Consequently, each upper-air report was arbitrarily truncated at 700 mb.

The surface observations and the upper-air reports were integrated on one tape by numeric time groups and organized

by location. The five years of data were subdivided into two seasons, designated "dry" and "wet". This classification was prompted by the fact that west coast weather, especially California, has two dominant seasons characterized by a generally dry summer period and a wet winter period. The so-called "dry" season consisted of the six months from April through September while the remaining six months, October through March, comprised the "wet" season. Initial attempts to study the data by months instead of by seasons was unsuccessful because the monthly sample size of fog cases was often too small. (This was especially true for the summer months at Oakland, California.)

Nineteen meteorological parameters, derived from both the surface and the upper-air data, were selected for analysis. Since upper-air observations were made only twice a day, the nineteen parameters were calculated for the times of the upper-air soundings, namely 0400 PST and 1600 PST. Nevertheless, <u>each</u> 3-hourly surface report was checked for the occurrence of fog and such information was retained in the parameter "fog strength", FS. (A discussion of the parameters is found in section B.)

As the parameters were calculated, the reports were further classified into four categories, based on the occurrence or non-occurrence of fog over the previous three days, and whether fog was reported within the current 24-hour period. If fog (no fog) occurred between 1601 PST on one calendar day and 1600 PST on the following calendar day, that period

was classified as a "fog" day ("no-fog" day). If fog was reported on <u>any</u> surface observation in the 72 hours (3 days) prior to the current fog/no-fog day, that period was termed "fog history". If, on the other hand, no fog was reported during the last 72 hours, a "no-fog history" period had occurred. Using these definitions, the four categories shown in Table I were derived. Generally speaking, categories 1 and 2 depict the possible <u>onset</u> of fog since they have no-fog histories, while categories 3 and 4 depict the possible <u>dispersion</u> of fog since they have fog histories.

The surface observations and upper-air data were now in a form which could be easily analyzed. Application of the discriminant analysis technique required the data to appear in two or more groups. The categories with common histories and opposite current fog designations were concatonated and fed into BMD07M in order to develop discriminant functions. For example, categories 1 and 2 (3 and 4) were used together where group 1(3) consists of "foggers" and group 2(4) consists of "no-foggers" in the current 24-hour period.

1. <u>Data Limitations and Special Considerations</u>

In any set of data there are always certain problems or limitations which must be reconciled or at least recognized. The most obvious restriction in this study was that the data covered only a five-year period (July 1968 to June 1973) and is given for just three west coast stations. These stations are separated by hundreds of miles and extend over 15 degrees of latitude. Also, recall that the surface observations were

made at three-hour intervals (0100, 0400, 0700, 1000, 1300, 1600, 1900 and 2200 PST), while the upper-air soundings were launched only twice a day (0400 and 1600 PST). It is important to realize that although fog may have occurred during a 24-hour period, say at 1000 PST, a full list of the parameters used for fog discrimination was available only at the sounding times, 0400 and 1600 PST. Considerable amounts of fog were reported at times intermediate to the upper-air data. This implies that significant changes in the existing sounding, especially in the marine layer, may have occurred in the interim, resulting in the formation of fog. These subtle changes would not be reflected necessarily in either the upper-air or surface observations for that fog day.

Several other limitations of the data set should be mentioned. First of all, if any information field in either the surface observations or the radiosonde soundings was missing in a reporting period (0400 or 1600 PST), that report had to be discarded. Unfortunately, missing data or a missing report caused a gap in the 72 hours of "fog history" and resulted in a loss of three days of information. Nevertheless, only about five percent of all the reports were rejected as a result of missing data. Another restriction which the data set imposed upon this research was that the broad synoptic picture was not considered. That is, sounding stations were not used to derive advective quantities or define air-mass boundaries, nor were synoptic charts employed. Furthermore, the sea-surface temperature (SST)

data taken from the Fishing Information Bulletin Supplements may not always be the most representative SST nearest the surface station. Although the SST changes rather slowly, a bi-weekly average SST can be inaccurate, especially in the summer months when solar radiation can result in significant temperature changes. The Oakland station SST was a special problem because the station is located on the east side of San Francisco Bay, several miles from the ocean regime. The sea-surface temperatures nearest the bay outlet were used, since the marine fog which forms offshore and affects Oakland generally enters through this opening.

One final special consideration was recognized in San Diego where the surface observation station (Lindberg Field) and the upper-air station (Montgomery Field) are not colocated. The radiosonde launch site is about 5.4 miles inland from Lindberg Field and is elevated 124 meters above sea level (or about 115 meters above the surface station). Under these circumstances a low-level inversion within the 124-meter layer could exist and yet not be shown on the sounding. McClure felt that in fog situations where inversions did not exist, but seemingly should have, there may have been an inversion near the sea surface. Consequently, in this study a special procedure was implemented to "bogus in" a surface inversion under the proper circumstances. If the surface temperature at Montgomery Field (upper-air station) was equal to or greater than the surface temperature at Lindberg Field (surface observation station) an isothermal condition or low-level inversion was said to have

existed. If the sounding had no inversion shown, the thickness of the low-level inversion was taken to be the difference in elevation between Montgomery and Lindberg Fields (124m-9m=115m). It is recognized that this is an artificiality and that other natural influences may account for these differences, such as the nature of the underlying surface and the difference between the marine air and urban environments.

B. DISCUSSION OF THE FOG/NO-FOG DISCRIMINATION PARAMETERS

The selection of the meteorological parameters to be used as fog discrimination variables was facilitated by previous researchers in this subject. The three non-diurnal indices developed by Leipper (1948) as fog forecasting aids in San Diego were adopted with only minor modifications for use in this study. McClure's thesis (1974) provided information about three important inversion parameters: height of the inversion base (also one of Leipper's indices), thickness of the inversion layer, and the temperature gradient within the inversion layer.

Using the works of Leipper and McClure as guidance, nineteen initially selected parameters were chosen or computed from the surface observations and upper-air data. These parameters are defined as follows (all temperatures in degrees Celsius, heights in meters, wind speeds in knots and pressures in millibars):

1. TB: the temperature at the <u>base</u> of the inversion if an inversion exists, otherwise zero.

2. TT: the temperature at the top of the inversion if an inversion exists, otherwise zero.

3. SI: the strength of the inversion, measured as the difference between the temperature at the top of the inversion and the temperature at the base of the inversion (TT-TB=SI), if an inversion exists, otherwise zero.

4. HB: the height of the base of the inversion if an inversion exists, otherwise zero.

5. HT: the height of the top of the inversion if an inversion exists, otherwise zero.

6. THK: the thickness of the inversion, measured as the difference between the height of the top of the inversion and the inversion base (HT-HB=THK), if an inversion exists, otherwise zero.

7. DIR: the direction from which the wind is blowing at the 950-mb level.

8. SPD: the wind speed at the 950-mb level.

9. TI: the temperature index, measured as the difference between the temperature at the top of the inversion (or the surface dry-bulb temperature if there is no inversion) and the sea-surface temperature (TT(or TDB)-SST=TI).

10. WDB: the surface wet-bulb depression, measured as the difference between the surface dry-bulb and wet-bulb temperatures (TDB-TWB=WBD).

11. DPD: the dew-point depression, measured as the difference between the surface dry-bulb and dew-point temperatures (TDB-TDP=DPD).

12. WET: the surface moisture index, measured as the difference between the dew-point and the sea-surface temperatures (TDP-SST=WET).

13. TDB: the surface dry-bulb temperature.

14. TWB: the surface wet-bulb temperature.

15. TDP: the surface dew-point temperature.

16. SST: the sea-surface temperature.

17. RH: the surface relative humidity.

18. SLP: the sea-level pressure.

19. FS: the fog strength; an integer number from 0 to 4 indicating the number of three-hourly surface observations during a twelve-hour period (from 0400-1600 PST or 1600-0400 PST) reporting fog.

The notation used to express the parameters and their relative day and time within the three-day history period is quite simple. The pre-subscript denotes the day during this period, while the post-subscript denotes the hour of observation (0400 or 1600 PST). Examples of this notation are as follows:

$_1HT_{16}$ = the height of the top of the inversion, taken from the first day of history and the 1600 PST report. (This would be the most recent observation in the history period.)

$3^{SI}04$ = the strength of the inversion, taken from the <u>third</u> day of history and the 0400 PST report. (This would be the oldest observation in the history period.)

In addition to the nineteen basic parameters described above, 12-, 24-, and 48-hour <u>time differences</u> in each of these variables were calculated using the three days of "history" associated with a fog occurrence. Because of the BMD07M program restriction of 80 variables there could be computed only 76 (of a possible 95) 12-hour differences, 76 24-hour differences and 38 48-hour differences from the total list of 114 (i.e., 6x19) parameters for each day. These differences can be shown schematically as follows:

12-hour differences

3 days of history associated with a fog occurrence			
		1600	(19 variables)
	1		
		0400	"
	2		
		1600	"
	3		
		0400	"
	4		
		1600	"
	5		
		0400	"

5x19=95 possible differences

24-hour differences

		1600	(19 variables)
	1	0400	"
2		1600	"
	3	0400	"
4		1600	"
		0400	"

4x19=76 possible differences

48-hour differences

1600 (19 variables)

0400 "

1 1600 "

2 0400 "

1600 "

0400 "

2x19=38 possible differences

Examples of the notation used to represent these differences are:

$\Delta_1 TB_{16-04}$ = the first (1600-0400) 12-hour difference in the temperature at the base of the inversion.

$\Delta_2 TB_{16}$ = the second (1600-1600) 24-hour difference in the temperature at the base of the inversion.

$\Delta\ TB_{04}$ = the (0400-0400) 48-hour difference in the temperature at the base of the inversion.

The time differences in the nineteen basic parameters are considered to be important since they allow for the influence of persistence, advection and other physical changes in the variables. Thus, the analyst can, at least, theoretically, project "trends" (time differences) of the parameters ahead in time for the purpose of developing a forecast.

C. DISCRIMINANT ANALYSIS[3]

The use of linear discriminant analysis in this study has been of fundamental importance in the successful development

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[3]Taken from Chapter 23 (written by William R. Klecka) of Statistical Package for the Social Sciences, Norman H. Nie, et al, McGraw-Hill, 1970.

of classification equations for marine fog prediction. The objective of the analysis is to statistically distinguish between two or more categories of cases. In this research these categories (see Table I) were determined by the occurrence or non-occurrence of fog during three successive days, and whether fog was reported during the current 24-hour period. Thus, the groups "fog" and "no-fog" were established as previously described.

In order to distinguish between the fog and no-fog groups, the nineteen initially selected parameters and their time differences were used as "discriminating variables" to measure characteristics on which these groups are expected to differ. The mathematical objective of discriminant analysis is to weight and linearly combine the discriminating variables in some manner so that the groups are forced to be as statistically distinct as possible. In other words, one hopes to be able to "discriminate" between the groups in the sense of being able to tell them apart.

Discriminant analysis attempts to accomplish this by forming one or more linear combinations of the discriminating variables. These "discriminant functions" are of the form:

$$D_m = c_{m0} + c_{m1}V_1 + c_{m2}V_2 + \ldots + c_{mn}V_n \qquad (1)$$

where D_m is the discriminant score for group m, the c_{mj}'s are the coefficients with c_{m0} being the constant, and the V's are the raw values of the n discriminating variables

used in the analysis. There is always a separate equation for each group. Hopefully, the discriminant scores (D's) for the cases within a particular group will be fairly similar. Nevertheless, the functions are formed in such a way as to maximize the separation of the groups. Once the discriminant functions have been derived, the primary research objective of classification can be pursued.

Classification is the process of identifying the group to which a fog/no-fog case is most likely to belong when the only information known is the case's values on the discriminating variables. The classification procedure involves the use of a separate linear combination of the discriminating variables for each group. These produce a probability of membership in the respective group, and the case is assigned to the group with the highest probability of occurrence. One problem with this type of classification procedure is that the rule of highest probability defines a very strict dividing line. A .51 probability of a fog occurrence versus a .49 probability of no fog would necessarily lead to a fog classification, yet the situation is not really all that clear. A Bayesian adjustment of the posterior probabilities is often desirable when the costs of misclassification into certain groups are high, or when the groups are of grossly different sizes. In this study the posterior probabilities were not adjusted.

During the analysis phase of this study the primary use of classification was to test the adequacy of the derived

discriminant functions. By classifying the fog and no-fog cases used to derive the functions in the first place and comparing predicted group membership with actual group membership, one can empirically measure the success in discrimination by observing the proportion of correct classifications.

The BMD07M program used in this research is a stepwise linear discriminant analysis routine which can accept a maximum of 80 discriminating variables. Since there are generally more variables available than are necessary, the stepwise analysis procedure is very helpful. It begins by choosing the single best-discriminating variable as determined by the selection criterion. A second discriminating variable is selected as the variable best able to improve the value of the discrimination in combination with the first. The third and subsequent variables are chosen in a similar manner according to their ability to contribute to further discrimination. At each step, variables already selected may be removed if they are found to reduce discrimination when combined with the more recently selected variables. This process continues until the remaining variables are no longer able to contribute significantly to further discrimination.

The stepwise analysis procedure just described has several test criteria which control the entry or removal of variables from the discrimination equation. Ultimately, the selection criterion is determined by the F ratio or

F value. The F value is the likelihood ratio of equality on the test variable over all the groups (two groups in this study), given the distribution produced by the variables already entered. In other words, the "F-to-enter" value is a test for the statistical significance of the amount of centroid separation added by this variable above and beyond the separation produced by the previously entered variables. At each step in the BMD07M program there is a similar test made of all variables already selected which have an inclusion level of one (the inclusion-level default option of one was used throughout this study). Here, the test is whether the particular variable still adds a significant amount to the group separation, given the other variables now in the equation. As more variables are chosen, it is possible that some of those entered earlier will no longer be contributing. This occurs because the information that they contain about group differences is now available in some combination of the other included variables. The contribution is measured by the "F-to-remove", which is an F test of the discrimination power currently added by the variable in question. If a variable already entered has an F-to-remove value less than one (again, the default option was used), it will be removed from the equation.

The BMD07M program computes unstandardized coefficients in the classification functions, thus making analysis and interpretation of such coefficients difficult. The unstandardized coefficients do not report the relative importance

of the variables since they have not been adjusted for the measurement scales and variability in the original variables. However, the unstandardized discriminant function coefficients can be easily utilized to find the fog/no-fog probability. In order to do so one first computes the discriminant score by multiplying the coefficients by the raw values of the associated variables, summing them together, and adding a constant to adjust for the grand means. This process is represented by Eq. (1). Then the posterior probability of case k having come from group m is:

$$p_{m,k} = \frac{p_m \exp(D_{m,k})}{p_f \exp(D_{f,k}) + p_{nf} \exp(D_{nf,k})} \qquad (2)$$

where m = a fog or no-fog day (f or nf)

p_m = the prior probability of group m

$D_{m,k}$ = the discriminant score for case k of group m.

In this study the prior probabilities of belonging to either the fog or no-fog group were taken to be equal, so p_m was 0.5. Some discriminant analysis programs allow for automatic adjustments to the prior probabilities on the basis that such probabilities are proportional to the number of cases in each group, i.e., cases will be more likely assigned to a larger group. The BMD07M routine does not have an automatic adjustment feature, but manual changes in the prior probabilities can be accomplished.

A wealth of statistical information can be derived from the BMD07M computer program--much more than this researcher

required. The information generally used in this study consisted of:

1. Group means and standard deviations
2. At each step:
    a. Variables included and F value to remove
    b. Variables not included and F value to enter
3. After each of the first seven steps and after the last step the classification functions were printed
4. The posterior probability of coming from each group was computed for each case
5. Summary table. For each step of the procedure the following were utilized:
    a. Variable entered or removed
    b. F value to enter or remove
    c. Number of variables included

D. ANALYSIS ROUTINE

After the data had been organized by location, season and fog category, the job of analysis was finally initiated. Since considerable fog research has been done in the San Diego area (see Section II), this study began here.

For each location and for both the "dry" and "wet" seasons, the fog and no-fog cases of categories 1 and 2 (and later 3 and 4) were combined and read into the BMD07M routine. It is important to remember the program restriction of a maximum of 80 discriminating variables, since this limitation influenced the analysis methodology. Associated with

each fog or no-fog occurrence were 3 days (six reporting periods) of history, listing a total of 114 variables (6 reports x 19 parameters = 114 variables). Also recall that there were the 12-, 24-, and 48-hour time differences of these variables which were available, thus adding another 209 possible fog discriminators. However, for any one computer program no more than 80 of these variables could be utilized.

In order to test the discriminating potential of all the possible variables, seven separate analysis programs were completed for each location, season and category pair (1 and 2; 3 and 4). These programs differed from one another by virtue of the variables being read into the BMD07M routine and are described as follows:

1. The 19 initially selected parameters for only the first <u>two</u> days of history, but both 1600 and 0400 PST reports were used.
2. The 19 basic parameters for all 3 days of history, but only the <u>1600</u> PST reports were used.
3. The 19 basic parameters for all 3 days of history, but only the <u>0400</u> PST reports were used.
4. Only the 12-hour time differences of the 19 basic parameters were used (four 12-hour differences).
5. The 24-hour time differences for only the <u>1600</u> PST reports were used.
6. The 24-hour time differences for only the <u>0400</u> PST reports were used.

7. The 48-hour time differences for both reporting periods were used.

Each of these computer programs executed the discriminant analysis routine with the available variables and printed a summary table listing the discriminating variables in order of entrance and the classification functions. After completing these jobs for both seasons (and for a given fog category pair), the best seven or eight discriminating variables were selected from each program and put in a list. Any of these variables which may have been duplicated between, say, programs #1 and #3 (see list above), or between wet and dry seasons were discarded. Finally, the "best" 80 discriminating variables were computed in a "composite" program for final analysis. This composite program was executed for both seasons and resulted in the final classification functions for a given location and fog category pair. Then the entire process was repeated for the other fog category pair (3 and 4). Thus, for each location a minimum of 32 discriminant analysis programs were executed in order to build the final classification equations. When using these equations one can calculate the percentage probability of fog/no fog over a 24-hour period beginning at 1601 PST on the current calendar day.

V. ANALYSIS RESULTS

A. INTRODUCTORY REMARKS

The analysis results of this research are presented largely in tabular form. For each west coast station studied there are three different types of tables. The first type shows the number of usable fog and no-fog "cases" (sometimes called "foggers" or "no-foggers") for each analysis category. A usable fog (no-fog) "case" is simply a fog (no-fog) day for which there are a complete list of parameters. The second type of table presents the classification functions, the variables utilized, and their associated F values. Recall that the F value (F ratio) shows the relative importance of the variable in question to the existing equation. The F values shown in the tables are those for the final classification equation. Thus, in general, the larger the F value (relative to unity) for a given variable, the greater that variable contributes to the discrimination (centroid separation) between the fog and no-fog groups. The third type of table shows the season and category for a given location, and the percentage of fog and no-fog cases correctly classified by the discriminant functions.

It is important to remember that the stepwise discriminant analysis procedure results in an optimal set of variables being selected and that the initially-best discriminating variables are chosen first. Therefore, in the

tables presenting the classification functions the variables are listed in order of decreasing importance according to initial entry. Where a variable had been entered and was subsequently removed there appears a remark indicating the step in the program that the variable was deleted.

B. SAN DIEGO RESULTS

Tables II and III show the number of fog and no-fog cases for the San Diego dry and wet seasons, respectively. During the dry season the fog cases comprise only 15.5% of the total number of cases, while during the wet season over 28% were fog days.

Table IV presents the fog and no-fog classification functions for the dry season, categories 1 and 2. The F values indicate that the two most important discriminating variables in the final equations are the temperature index (${}_{1}TI_{04}$) and the inversion thickness (${}_{1}THK_{04}$) taken from the most recent 0400 PST observations. In this case the mean ${}_{1}TI_{04}$ for the foggers was approximately 4.0 C, while the no-foggers had a mean of about 1.6 C. This implies that a relatively large temperature difference between the air temperature (at the surface or inversion top) and the SST prevailed just prior to most fog occurrences. This result generally supports Leipper's (1948) temperature index range values found in San Diego. The mean values of the inversion thickness for the fog and no-fog cases differed only slightly (385.7 m versus 362.3 m), but the thickness was greater for the fog reports.

The classification functions for the wet season, categories 1 and 2, are given in Table V. Although the moisture index ($_1WET_{16}$) and the inversion strength ($_2SI_{04}$) were entered as the first two variables, they were subsequently removed. When they were later re-entered they made only a small contribution to the overall discriminating power of the final equations. In this program the ultimate best three variables are the wet-bulb depression ($_1WBD_{16}$), the height of the top of the inversion ($_3HT_{04}$), and the temperature index ($_1TI_{16}$) at 1600 PST. The mean wet-bulb depression for the no-foggers was almost 1.3 degrees greater than that of the fog reports. The three-day-old HT value was, on the average, 81 m higher for the no-fog cases. The TI mean values differed by about 1.1 C (3.3 versus 2.2), and again this value was usually larger for the fog reports.

Table VI shows the classification functions for San Diego during the dry season for categories 3 and 4. Recall that categories 3 and 4 differ from 1 and 2 in that they have a history of fog. Furthermore, categories 3 and 4 should give some clue as to the parameters of interest in fog dispersion. The F values once more identify the temperature index ($_1TI_{04}$) as being very important to the final equations, and surprisingly, so is the three-day-old wind direction ($_3DIR_{04}$). As was seen before, the mean TI was significantly higher for the foggers than the no-foggers. In this instance the difference was about 2.5 degrees (i.e., 5.5 C for fog versus 3.0 C for no-fog). In San Diego the temperature index appears to be an important fog/no-fog discrimination parameter.

The 950-mb wind direction mean values indicate that three days before a fog occurrence the wind was southeasterly (about 126°), whereas prior to no-fog days the wind was generally from the southwest (207°). It should be noted, however, that the standard deviation for these wind directions was about 120 degrees. Therefore, solid conclusions as to the significance of this result cannot be made without further analysis on a broader data base. Other important discriminating parameters shown in Table VI are a 48-hour change in the 1600 PST wet-bulb temperature (ΔTWB_{16}), a 48-hour change in the 0400 PST wet-bulb depression (ΔWBD_{04}), and a 12-hour change in the temperature index ($\Delta_1 TI_{04-16}$).

The San Diego wet season classification functions for categories 3 and 4 are presented in Table VII. The most capable discriminators in these equations are the wet-bulb depression (${}_1WBD_{16}$), the inversion-base height (${}_1HB_{16}$), and the fog strength (${}_1FS_{16}$), all measured at 1600 PST. The statistics for the wet-bulb depression mean values are nearly identical with those mentioned for categories 1 and 2 during the wet season. The no-fog reports averaged over 1.3 degrees higher than those of the fog cases (4.3 C versus 3.0 C respectively). This result appears to be consistent for all categories in the San Diego winter season. The mean values of the inversion-base height exhibit dramatic differences between the fog and no-fog cases. In fog situations the base heights were about 168 m, whereas the heights for no-fog situations were 536 m. Thus, as the fog regime begins to

dissipate, the base of the inversion rises. This is in agreement with Leipper's model for San Diego winter fogs (Leipper, 1948).

The fog strength (FS) parameter can be a significant discriminator only in categories 3 and 4 where there is a history of fog. In this case, during the wet season the mean FS value for 1600 PST was nearly 0.88 for fog cases and 0.26 for no-fog reports. This simply suggests that fog <u>persistence</u> is likely to occur in winter. That is, fog is likely to occur in one of the three-hourly surface observations in successive twelve-hour periods.

Table VIII shows the San Diego fog and no-fog discrimination percentages for the seasons and category pairs. The discriminating capability of the category 3 and 4 equations is better than those for 1 and 2, especially for fog classification. Overall, the weighted average fog discrimination percentage was about 82.2, while the no-fog percentage was nearly 81.3.

C. OAKLAND RESULTS

The occurrence of fog in Oakland's summer (dry) season is indeed infrequent. For the five-year data period of this study there were only a total of 32 fog days during this season, as shown in Table IX. This amounts to less than four percent of the total cases. Fog occurrences in the wet season (shown in Table X) were more common--about 24% of the cases reported fog.

Table XI presents the fog and no-fog classification functions for the Oakland dry season, categories 1 and 2. As the F values reveal, the best-discriminating variables in the final equations are the 24-hour change in the 1600 PST inversion thickness ($\Delta_1 THK_{16}$), a similar time difference in the relative humidity ($\Delta_1 RH_{16}$), and the second (0400-1600) 24-hour change in the temperature index ($\Delta_2 TI_{04}$). It is interesting to note that the most important variables in this equation are all 24-hour <u>time differences</u>. With the exception of one wind speed variable ($_2SPD_{16}$), the nineteen basic parameters themselves contribute very little to the fog/no-fog discrimination.

The 24-hour thickness change mean values showed that there usually was a <u>decrease</u> in the 1600 PST inversion thickness just prior to a fog occurrence. The $\Delta_1 THK_{16}$ average for the fog reports was about -132 m, whereas the no-fog value was 2.6 m (a negligible increase). Although the standard deviations for the two groups average about 265 m, the means clearly indicate a reduction of the inversion thickness which was an unexpected result. Since this season contained only 25 fog reports, analysis of a larger data set seems necessary in order to be certain of this thickness relationship.

Another surprising result in this analysis was that the 24-hour relative humidity change ($\Delta_1 RH_{16}$) for the fog reports was an average -0.18%. Although the mean change is very small, one would normally expect a moderate <u>increase</u> in the

relative humidity prior to fog. $\Delta_1 RH_{16}$ for the no-fog cases was almost zero, and the standard deviation for both groups exceeded 2.0.

The mean values of the 24-hour change in the temperature index ($\Delta_2 TI_{04}$) reflected an increase (almost 1.5 C) for the fog cases and a very slight decrease (-0.06 C) for the no-fog cases. This result appears to be consistent with San Diego observations; several days prior to fog development the inversion intensifies which generally leads to an increase in the temperature index.

The classification functions for Oakland's wet season, categories 1 and 2, are given in Table XII. Here the first two variables entered in the stepwise discriminant analysis remained the best variables in the final equations. Both of these parameters were from the most recent 1600 PST observation and are the temperature at the top of the inversion ($_1TT_{16}$), and the relative humidity ($_1RH_{16}$). The means of the TT values were 8.7 C for foggers and 5.5 C for the no-foggers. From this result one might infer that the inversion is either thicker or more intense, or possibly both. The RH mean value for the fog cases was almost ten percent higher than for the no-fog cases (73.5% versus 63.6%).

Of tertiary importance as a discriminating variable is the first (0400-1600) 12-hour change in the temperature of the inversion base ($\Delta_1 TB_{04-16}$). The mean values for the fog and no-fog cases were approximately 3.2 C and 1.4 C, respectively. Although the inversion base showed a 12-hour warming

tendency for both groups, the average increase was more than twice as great for the foggers. The reason for this warming tendency at the base of the inversion is not fully understood by this researcher, especially since this was over a 12-hour period (0400-1600) during which diurnal cooling usually occurs.

Table XIII shows the classification functions for Oakland during the dry season for categories 3 and 4. As the F values indicate, the three most capable discriminators in these equations are the fog strength ($_2FS_{16}$), the 950-mb wind speed ($_2SPD_{16}$), and the wet-bulb temperature ($_2TWB_{16}$). Curiously, all three of these variables were taken from the 1600 PST reports which were two days old. It is important to note that there were only seven fog reports for this season and category, compared to over eleven times as many (78) no-fog cases.

Interestingly, the fog strength mean for the fog cases (0.14) was less than half of the mean for the no-fog cases (0.36). This is just the opposite that one might expect if fog persistence had occurred. Because the fog and no-fog cases were so disproportionate, perhaps some adjustment in the prior probabilities reflecting this imbalance would moderate or change this result and remove a potential statistical bias.

The wind speed parameter showed less than one knot difference between the mean values of each group--3.9 knots for foggers and 4.8 knots for no-foggers. The wet-bulb

temperature averages were about 16.0 C and 14.3 C for the fog and no-fog cases, respectively. Once again, a larger data sample of reports is required to prove whether these differences are really significant.

The Oakland wet season classification functions for categories 3 and 4 are presented in Table XIV. The best discriminator in these equations is the temperature at the inversion top, measured at 1600 PST ($_1TT_{16}$)--the same as for the category 1 and 2 analysis during this season. The mean values for this parameter indicate nearly a 4.3 degree spread between the groups--about 10.0 C for the foggers and 5.7 C for the no-foggers. The identical inferences may be made since the tendency was equal to that of the category 1 and 2 result.

Two other important discriminators in this program are the 48-hour change in the 1600 PST 950-mb wind speed (ΔSPD_{16}), and the 0400 PST height of the inversion top ($_1HT_{04}$). The average wind speed change was only a one-third knot decrease for the fog cases and a 0.6 knot increase for the no-fog reports. Nevertheless, in this data set the nearly one knot difference was found to be statistically significant by the BMD07M program. The mean values for the height of the inversion top for foggers and no-foggers were 566 m and 637 m, respectively. Although the difference between the group means was only 71 m, the tendency for a lower near-surface inversion prior to fog occurrences is evident.

Table XV shows the Oakland fog and no-fog discrimination percentages for the seasons and category pairs. The high discrimination score for the dry season, categories 3 and 4, was largely due to the unusually small number of fog and no-fog cases. If the BMD07M program had been allowed to continue until the F-to-enter value dropped below 1.0 (as was done with all other equations), the resultant equation would have had 30 variables (after 48 program steps!) and could achieve a "perfect" discrimination score. However, thirty variables was considered to be an excessive number for this small data set and the program was limited to twenty-one steps which included the final fifteen variables shown in Table XIII. The overall weighted fog discrimination percentage was above 77.4, while the no-fog percentage was 76.8.

D. QUILLAYUTE RESULTS

Whereas the occurrence of fog in Oakland was a rarity in summer, Quillayute, Washington has fog as a fairly frequent visitor throughout the entire year. In fact, for the period of this research exactly 50% of the dry-season reports and nearly 54% of the wet-season reports were fog cases. The number of fog and no-fog cases for these two seasons are shown in Tables XVI and XVII. It is likely that in this area a significant percentage of fog occurrences were associated with frontal activity, since most mid-latitude storms track across the Washington coast.

Table XVIII presents the fog and no-fog classification functions for the Quillayute dry season, categories 1 and 2. There are many variables with relatively large F values, but the three best discriminators in these equations are the most recent 24-hour change in the 0400 PST temperature index ($\Delta_1 TI_{04}$), the second 12-hour change (0400-1600 PST) in the temperature index ($\Delta_2 TI_{04-16}$), and the 950-mb wind direction measured at 0400 PST ($_1 DIR_{04}$). Also notice that the first two variables entered in the stepwise discriminant analysis ($\Delta_2 THK_{04}$ and ΔWET_{16}) were subsequently removed.

The importance of the temperature index parameter and its time differences is again demonstrated by the fact that they are the top two discriminators in these equations. The mean values for $\Delta_1 TI_{04}$ were about 1.4 C for foggers and 0.6 C for no-foggers. Thus, the 24-hour change in the temperature index was significantly higher for fog situations. This result is likely to be caused by increasing temperatures at the top of the inversion which is associated with a strengthened inversion. The mean values for $\Delta_2 TI_{04-16}$ were about -5.2 C and -5.6 C for the fog and no-fog cases, respectively. Although the BMD07M program found some statistical significance in the group means' difference, the standard deviations were fairly large (about 2.4 for both groups) and very few conclusions can be made about this parameter.

The 950-mb wind direction averages were about 214° for fog reports and 186° for no-fog cases. Again the standard deviations were large (nearly 115° for both groups), but the

mean wind direction prior to most fog occurrences had a component from the west. This implies that the fog was generally advected landward by the prevailing southwesterly flow.

The classification functions for Quillayute's wet season, categories 1 and 2, are given in Table XIX. The first variable entered, the 1600 PST 950-mb wind speed (${}_{1}SPD_{16}$), was the best-discriminating parameter in these equations. The mean wind speed for the fog cases was over 9.0 knots, while the no-fog mean was 5.7 knots. The cause for the significantly higher wind speed associated with fog occurrences is not clear. The supposition that these speeds are related to pre-frontal fog appears to be disproved by two other important discriminators.

The two-day-old wind direction taken at 0400 PST (${}_{2}DIR_{04}$) was the second best-discriminating variable. Surprisingly, the mean wind directions for both fog and no-fog groups were from the southeast quadrant--the values were approximately 155° and 125°, respectively. The third important variable was the sea-level pressure measured at 1600 PST (${}_{2}SLP_{16}$). The group means showed a significant pressure difference of about 2.7 mb. The average SLP for foggers was almost 1019.6 mb, while the no-foggers had an average of 1016.9 mb. This researcher was unable to find an adequate explanation for this last result without supplementary information.

Table XX shows the classification functions for Quillayute during the dry season for categories 3 and 4. The F values indicate that the first-entered variable, the 1600

PST relative humidity (${}_{1}RH_{16}$), is by far the most important discriminator in these equations. The mean relative humidities for the fog and no-fog cases were 73.5% and 60.4%, respectively. It appears logical that as fog approaches the station the relative humidity will increase. The 13.1% spread between the average relative humidities provided easy discrimination between the two groups.

Three other variables in Table XX stand out as significant in the classification functions. These are the temperature index (${}_{1}TI_{16}$), the 950-mb wind direction (${}_{1}DIR_{16}$), and the moisture index (${}_{1}WET_{16}$), all derived from the most recent 1600 PST observations. The TI mean values were -2.8 C for foggers and about -1.7 C for no-foggers. The fact that the fog cases had a larger negative TI is rather surprising since one would expect that the closer the air temperature is to the SST, the greater the chance of fog. The negative TI indicates that the air temperature is usually lower than the SST.

The mean wind directions for the fog and no-fog groups were both from the southwest (237° for foggers and 231° for no-foggers), and showed such a minor difference that one wonders why it was chosen as a meaningful discriminator. The moisture parameter (${}_{1}WET_{16}$) seems to have greater theoretical meaning in this program. The mean moisture values were approximately -8.3 C for fog cases and -9.9 C for no-fog reports. Recall that the moisture index is the difference between the dew-point and sea-surface temperatures. In the

Quillayute dry season the dew-point temperature is nearly always well below the SST. However, during fog situations the difference is smaller, which implies a greater likelihood of fog formation.

The Quillayute wet season classification functions for categories 3 and 4 are presented in Table XXI. In these equations the relative humidity parameter (${}_1RH_{16}$) again stands out as the most capable discriminator. As before, the difference between the groups' averages is about 13%, but in the wet season the relative humidities are higher--almost 87.0% for foggers and 74.2% for no-foggers.

The second- and third-best discriminating variables are the 1600 PST temperature index (${}_1TI_{16}$) and the 0400 PST wet-bulb depression (${}_1WBD_{04}$). The TI statistics showed fairly large negative mean values--a -7.7 C for fog cases and a -8.1 C for no-fog reports. During the winter season one should expect larger negative values for this parameter in the colder, more northerly latitudes. Nevertheless, the slightly smaller TI for the foggers indicates a greater probability of a fog occurrence. The wet-bulb depression means values showed only a minor spread of 0.1 degree--the foggers averaged 0.54 C while the no-foggers were about 0.64 C. Although the difference was small, the discriminant analysis routine found that it made a significant contribution in these classification functions.

Table XXII presents the Quillayute fog and no-fog discrimination percentages by season and category pairs. The

results for the category 1 and 2 analyses are considerably better than for 3 and 4. This was probably due to the much smaller number of cases in the 1 and 2 category. The overall weighted discrimination percentage was above 74.9 for the fog cases and nearly 75.5 for the no-fog reports.

The cumulative average discrimination percentages for all three stations analyzed in this study resulted in 78.2% for all fog cases and over 77.8% for all no-fog cases.

E. SOME TEST RESULTS

In order to test the discriminating capability of some of the classification equations three years of additional data were utilized. The Naval Weather Service Detachment, Asheville, North Carolina again provided the airways surface observations and radiosonde soundings, while more SST information was extracted from the Fishing Information Bulletin Supplements. The test data covered the period from 1 July 1965 through 30 June 1968--i.e., the three years preceding the initial analysis period.

Primarily due to time considerations, only the San Diego classification equations were tested. The data were prepared by season and categories in the manner previously described (see Section IV, subsection A). The number of fog and no-fog cases listed by category for the test data dry and wet seasons are shown in Tables XXIII and XXIV, respectively. A testing computer program was developed which would form the fog and no-fog probabilities (see Eqs. (1) and (2)) and classify each case in the same manner as the BMD07M routine.

Table XXV shows the percentage of correct discriminations which resulted from testing the San Deigo classification equations on the independent data set. Although the discrimination percentages were considerably reduced from the dependent analysis sample, the outcome was generally acceptable except for the dry season fog prediction capability. The reason for this failure is not known. The overall weighted fog discrimination percentage for the San Diego test data was above 68.4, while the no-fog percentage was nearly 74.3.

By comparing the numbers of fog and no-fog cases in Tables III and XXIV, one will note that the relative proportions of cases are similar. Thus, it seems unlikely that unusual group sizes could be a factor in the dry season's poor discrimination capability. Perhaps better results could be obtained if the BMD07M program prior probabilities were made proportional to the number of cases in each group. This would increase the likelihood of being assigned to the larger group. Another alternative would be to make a Bayesian adjustment to the probabilities of group membership, especially when the groups are of grossly different sizes as was found in both San Diego and Oakland.

From Table XXIII one can find that during San Diego's dry season only 11% of the total number of cases (for the test data period) were fog reports. During the wet season (see Table XXIV) about twice as many (22.5%) fog days occurred. From these statistics a forecaster might logically conclude that he would be correct almost 90% of the time in

the dry season by <u>never</u> predicting the occurrence of fog! Indeed, persistence and climatology forecast methods may be difficult to surpass, but other prediction tools are essential.

VI. PROCEDURE FOR APPLICATION OF THE CLASSIFICATION FUNCTIONS

One of the primary objectives of this study was to develop classification equations which could be utilized to forecast the daily probability of occurrence of marine fog at the three U. S. west coast stations analyzed. The classification functions presented herein provide a means for forecasting the probability of fog/no fog for a 24-hour period beginning at 1601 PST. In order to calculate these probabilities the forecaster must have:

1. The station's 3-hourly surface observations and the upper-air soundings for the last three days.

2. A reliable bi-weekly mean coastal SST near the station. (This is required to form the TI and WET parameters.)

3. A desk calculator or a small programmable computer.

The following step-by-step procedure is recommended for the proper application of the classification functions.

1. Note whether fog has occurred on any surface report in the last three days, starting with the most recent 1600 PST observation. If there has been such a fog occurrence, use the table for the current season (wet or dry), categories 3 and 4. If there is no history of fog, use the table labeled categories 1 and 2, for the current season.

2. Using the surface observations, the upper-air soundings, and the SST data, find the numeric value of each of

the variables listed in the table selected in step 1. (See the definitions of the variables in Section IV, subsection B.)

3. With the aid of a desk calculator or a computer multiply the raw values of the variables by their associated fog coefficients and add them together along with the constant. Do the same with the no-fog coefficients. These two sums are the discriminant scores, D_f and D_{nf} (see Eq. (1)).

4. To avoid problems in exponentiating discriminant scores which might be outside the allowable range,[4] one may do the following:

a. Select the minimum discriminant score between D_f and D_{nf}.

b. Subtract the minimum discriminant score from D_f. Let the result be called "DIFF".

(1) If DIFF is greater than or equal to -174.673, exponentiate DIFF.

(2) Otherwise, set DIFF equal to zero and then exponentiate.

Call the above result "PF".

c. Repeat step b using the <u>no-fog</u> discriminant score, D_{nf}, in place of D_f. Call this result "PNF".

5. Form the posterior probability of a fog occurrence by dividing PF by the sum of PF and PNF (see Eq. (2)). Then

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[4]The constant 174.673 is the largest power of e that the IBM 360 computer can represent. If using another computer this constant will vary.

the probability of no fog occurring is unity minus the probability of fog.

Appendix A presents a generalized FORTRAN program of the above procedure.

VII. CONCLUSIONS AND FINAL REMARKS

The primary goal of developing linear classification equations which may be used for forecasting the probability of marine fog at San Diego, Oakland, or Quillayute, has been accomplished. The ultimate capability of these equations has not been fully tested. Nevertheless, it is hoped that these discriminant functions may serve some useful purpose--if not for operational employment, then perhaps as a basis for further study.

One of the important by-products of the classification equations was insight as to which variables are the best fog/no-fog discriminators. The following is a brief summary of the most capable discriminating variables, listed in order of decreasing importance by location, season, and category pair:

SAN DIEGO

DRY (1+2):	${}_1TI_{04}$	${}_1THK_{04}$	Δ_2DIR_{16-04}	ΔWBD_{04}
WET (1+2):	${}_1WBD_{16}$	${}_3HT_{04}$	${}_1TI_{16}$	ΔTB_{04}
DRY (3+4):	${}_1TI_{04}$	${}_3DIR_{04}$	ΔTWB_{16}	ΔWBD_{04}
WET (3+4):	${}_1WBD_{16}$	${}_1HB_{16}$	${}_1FS_{16}$	ΔTI_{16}

OAKLAND

DRY (1+2):	Δ_1THK_{16}	Δ_1RH_{16}	Δ_2TI_{04}	Δ_2SI_{04-16}
WET (1+2):	${}_1TT_{16}$	${}_1RH_{16}$	Δ_1TB_{04-16}	${}_3DIR_{16}$
DRY (3+4):	${}_2FS_{16}$	${}_2SPD_{16}$	${}_2TWB_{16}$	Δ_1SI_{16-04}
WET (3+4):	${}_1TT_{16}$	ΔSPD_{16}	${}_1HT_{04}$	Δ_1SLP_{04-16}

QUILLAYUTE

DRY (1+2):	$\Delta_{1}TI_{04}$	$\Delta_{2}TI_{04-16}$	${}_{1}DIR_{04}$	ΔRH_{16}
WET (1+2):	${}_{1}SPD_{16}$	${}_{2}DIR_{04}$	${}_{2}SLP_{16}$	$\Delta_{2}TT_{16-04}$
DRY (3+4):	${}_{1}RH_{16}$	${}_{1}TI_{16}$	${}_{1}DIR_{16}$	${}_{1}WET_{16}$
WET (3+4):	${}_{1}RH_{16}$	${}_{1}TI_{16}$	${}_{1}WBD_{04}$	$\Delta_{1}SPD_{16-04}$

Several conclusions can be made about the discriminating parameters shown in this analysis summary:

1. The temperature index (TI) and several of its time differences are powerful discriminators, especially in San Diego and Quillayute. Since this index uses the SST as an "anchor point", reliable coastal SST data are very important. This may provide a clue as to why the TI is not particularly significant at Oakland. The SST data for this station was extracted from SST charts at a point just west of the San Francisco Bay entrance, supposedly where the marine fog might form and be advected shoreward. In retrospect, perhaps a bay water temperature would have been a better reference for the TI at this station.

2. The most recent relative humidity measurement (${}_{1}RH_{16}$) and its 24-hour change ($\Delta_{1}RH_{16}$) appear to be excellent discriminating variables in Quillayute for categories 3 and 4, and in Oakland for categories 1 and 2.

3. In Oakland's wet season, the 1600 PST temperature at the inverstion top (${}_{1}TT_{16}$) is a useful fog/no-fog predictor.

4. The 1600 PST wet-bulb depression is an important discriminator in San Diego during the wet season.

5. Two discriminating variables which were hoped to be of importance in the final classification equations were the strength of the inversion (SI) and the moisture index (WET). One will notice, however, that these parameters generally made only a relatively minor contribution to the discriminating capability of most equations. Several times the moisture index was entered into the regression equation first, indicating a large initial discrimination power, only to loose its importance as other variables were entered. Nevertheless, this researcher feels that the moisture index is still a worthwhile parameter and should be investigated in further research.

The discriminant analysis approach is certainly not a new research technique. In the past, multiple linear regression has been employed in numerous studies which require analysis of multivariate observations whose predictand was non-numerical. In the last decade, through the advance of computer technology, tremendous progress has been made in the rapid analysis of numerical and statistical information. Without the use of a high-speed computer and a sophisticated discriminant analysis program the completion of this research by a single individual within a reasonable time frame would be impossible. However, through the application of these powerful computational resources meaningful relationships can be determined and an enhanced fog-forecasting capability may be evolved.

VIII. RECOMMENDATIONS FOR FURTHER STUDY

The analysis results revealed several interesting and unexpected relations between various meteorological parameters and the occurrence or non-occurrence of marine fog at selected locations on the west coast of the United States. In order to evaluate the full significance of these parameters and attempt to improve the classification functions, the following recommendations are offered for future study.

1. A larger data base is needed in order to obtain a greater number of fog and no-fog cases for discriminant analysis. A distinct paucity of fog cases was noted in both San Diego and Oakland dry seasons. In such instances the BMD07M program may generate classification equations which have used a few anomalous occurrences (which, however, may be a significant portion of a small data set) for discrimination purposes. Such equations might not indicate the discriminating variables which are truly important to fog forecasting. Consequently, a ten-year data period is considered to be the minimum for best results using the discriminant analysis technique.

2. Make adjustments in the prior probabilities such that these probabilities are proportional to the number of cases in each group. Further experimentation with variable prior probabilities is necessary to test their effect on the selection of the fog/no-fog discrimination parameters and the final classification equations.

3. Expand the list of discriminating variables to include visibility, low cloud information and persistence parameters. Other wind levels should also be studied.

4. Refinement or re-definition of "fog" to include only those cases where visibilities are reduced to less than three miles (IFR conditions) may result in forecasts of greater operational importance. Some measure of relative fog intensity, such as "heavy" versus "light" fog may also enhance the forecast. However, a very large data base will be required for such refinements.

5. The use of better sea-surface temperature information is strongly recommended. Bi-weekly average SST data extracted from smoothed isotherm analyses are likely to be inaccurate. The SST data are important because a one- or two-degree temperature difference between the marine air and the underlying sea may be crucial in determining whether fog is expected to form, or in measuring its intensity. Reliable, daily SST information might make the temperature and moisture indices (TI and WET) better fog/no-fog discriminators.

6. With the use of a larger data set, one should try analysis on four seasons of the year instead of just two. Such a seasonal refinement may provide an enhanced fog prediction capability through the use of more representative classification functions.

7. Develop a method of stratifying the 24-hour forecast into two 12-hour periods (or smaller intervals) in an

effort to indicate more precisely the expected time of fog occurrence.

8. Since Oakland is somewhat sheltered from the marine-air influence by the coastal hills of San Francisco, data from a station closer to the coast should be used. The surface observations from such a station could be coupled with the Oakland upper-air sounding data.

Application of these refined analysis techniques to an enlarged data base would, hopefully, result in a significant improvement in marine-fog forecasting at the west coast stations of interest.

CATEGORY	HISTORY (3 DAYS)	CURRENT 24-HR PERIOD
1	NO FOG	FOG
2	NO FOG	NO FOG
3	FOG	FOG
4	FOG	NO FOG

TABLE I. FOG AND NO-FOG CATEGORIES

CATEGORY	NUMBER & CLASSIFICATION
1	50 FOGGERS
2	531 NO-FOGGERS
3	60 FOGGERS
4	180 NO-FOGGERS

TABLE II. SAN DIEGO DRY SEASON FOG AND NO-FOG CASES

CATEGORY	NUMBER & CLASSIFICATION
1	69 FOGGERS
2	407 NO-FOGGERS
3	108 FOGGERS
4	220 NO-FOGGERS

TABLE III. SAN DIEGO WET SEASON FOG AND NO-FOG CASES

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
ΔTWB_{16}	-0.69860	-0.94497	2.7169
${}_1TI_{04}$	-0.73689	-1.07313	23.6201
Δ_2DIR_{16-04}	0.01075	0.00646	9.2365
${}_1THK_{04}$	0.00125	0.00313	10.2577
ΔWBD_{04}	-1.23321	0.49745	8.9386
ΔDPD_{04}	0.34705	-0.27131	5.1529
ΔSLP_{16}	-0.36144	-0.17900	8.5494
Δ_2TWB_{04}	0.11503	-0.09174	1.9007
${}_2HT_{04}$	0.00153	0.00081	3.8738
${}_2SI_{04}$	0.01062	0.11482	3.7899
Δ_1TDP_{16-04}	1.19864	1.00863	2.9281
Δ_1TI_{16}	-0.41794	-0.54457	1.8798
${}_1TB_{16}$	-0.24155	-0.16593	4.2166
${}_1DIR_{04}$	-0.00005	0.00234	2.8459
${}_1DIR_{16}$	0.14416	0.13815	2.2897
${}_1TWB_{04}$	2.35226	2.24390	1.8560
Constant	-37.83261	-35.13945	

TABLE IV. SAN DIEGO DRY SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 1 AND 2

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_1WET_{16}$	(Removed at step 16, & later re-entered)		
${}_2SI_{04}$	(Removed at step 20, & later re-entered)		
${}_3SI_{16}$	1.22214	0.99060	2.9369
$\Delta_1 THK_{04}$	0.00375	0.00260	4.6784
$\Delta_2 WBD_{04-16}$	-1.64342	-1.27683	7.7045
$\Delta_2 TT_{04-16}$	(Removed at step 22)		
${}_1TWB_{04}$	2.40756	2.55562	3.4998
$\Delta_1 TI_{04-16}$	-1.13487	-1.29938	4.0756
${}_2DIR_{16}$	0.02395	0.02075	3.4434
${}_3HT_{04}$	0.00008	0.00134	10.5531
ΔTB_{04}	-0.07748	-0.19115	7.8624
${}_3TDP_{16}$	0.60771	0.49668	4.1412
${}_3TI_{04}$	-0.47578	-0.64106	4.0329
${}_1RH_{16}$	(Removed at step 25)		
${}_1TI_{16}$	2.17704	1.65256	9.7573
${}_3SPD_{16}$	1.17041	1.27535	1.9934
${}_1DIR_{04}$	0.01875	0.01652	2.4990
$\Delta_2 HB_{16-04}$	0.00054	0.00094	3.2675
${}_2SPD_{04}$	(Removed at step 31)		
${}_3TT_{16}$	0.19322	0.16090	1.5050
${}_1WBD_{16}$	-2.96269	-1.90545	12.1110
${}_1TDP_{16}$	1.05731	0.98900	2.0290
${}_1WET_{16}$	-3.10002	-2.83606	3.0366
ΔSI_{16}	0.06976	0.19479	1.5140
${}_2TI_{04}$	-1.85104	-1.68469	3.1752
${}_2SI_{04}$	1.48530	1.39985	1.6265
Constant	-40.16452	-40.49783	

TABLE V. SAN DIEGO WET SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 1 AND 2

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_{1}FS_{16}$	127.58673	126.82245	3.4129
${}_{3}DIR_{04}$	0.42659	0.43420	19.8636
${}_{1}WET_{16}$	(Removed at step 21)		
${}_{1}TI_{04}$	-23.87572	-24.84428	22.1792
${}_{1}FS_{04}$	-7.25344	-8.02159	7.1250
${}_{2}TT_{04}$	26.61739	26.73076	6.2731
ΔWBD_{04}	32.45081	30.04062	10.2524
ΔRH_{04}	10.95739	10.76887	4.3374
$\Delta_{1}SPD_{16-04}$	-38.42950	-38.25275	2.0741
$\Delta_{2}SPD_{04-16}$	24.53719	24.32675	3.0246
$\Delta_{2}TWB_{16}$	(Removed at step 19)		
$\Delta_{2}HB_{16-04}$	-0.01331	-0.01411	1.7733
${}_{3}SI_{16}$	(Removed at step 25)		
${}_{2}SPD_{16}$	75.30409	75.55360	4.1700
${}_{1}THK_{04}$	0.41899	0.42067	3.4352
${}_{1}SLP_{04}$	221.02830	221.20645	3.4470
$\Delta_{1}DIR_{16}$	-1.12342	-1.12795	1.4305
ΔTWB_{16}	-97.16171	-97.94383	12.1096
${}_{1}WBD_{16}$	39.62401	40.02596	6.3403
$\Delta_{1}TI_{04-16}$	68.23961	68.77629	10.1973
$\Delta_{2}TDB_{16}$	59.41071	59.89287	7.0221
${}_{3}TI_{16}$	17.00053	17.34978	4.3841
${}_{1}DPD_{04}$	-17.24670	-17.02985	1.7932
$\Delta_{2}RH_{04}$	-5.97035	-6.00543	1.2460
${}_{3}SI_{04}$	-24.14389	-23.99202	2.3931
ΔTI_{04}	-51.37943	-51.23575	1.3127
ΔHB_{16}	0.01494	0.01441	1.1024
Constant	-112260.12500	-112446.18750	

TABLE VI. SAN DIEGO DRY SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 3 AND 4

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
$_1WET_{16}$	(Removed at step 23)		
$_1FS_{16}$	0.27487	-0.50531	10.3541
$_1HB_{16}$	-0.04832	-0.04735	11.0117
ΔTI_{16}	-25.14560	-25.54906	8.6549
$_1THK_{04}$	0.15735	0.15587	3.6692
Δ_2TWB_{16}	(Removed at step 22)		
ΔSPD_{16}	16.75336	16.83115	3.5183
Δ_2DIR_{04}	0.01693	0.01492	3.8820
Δ_1SI_{16}	(Removed at step 19)		
$_1DIR_{04}$	-0.14458	-0.14257	1.9764
ΔTWB_{16}	-1.23822	-0.85878	4.6643
ΔRH_{16}	1.19872	1.13272	7.7717
Δ_2TDB_{16}	20.99492	20.64488	6.1341
Δ_2RH_{04}	-2.62901	-2.64525	2.2931
$_1SLP_{16}$	112.41910	112.31770	3.9060
ΔSI_{04}	-5.89893	-5.82536	3.2766
Δ_2TI_{04}	0.90936	0.79580	3.9585
Δ_2TI_{16}	-6.86152	-6.61983	2.9379
$_2TWB_{16}$	53.50967	53.32607	4.8779
$_1WBD_{16}$	20.14551	20.63298	14.2448
$_1TI_{16}$	-7.69770	-7.90987	4.3569
$_3SI_{16}$	-19.78639	-19.68510	1.0576
Δ_2TT_{16-04}	-1.14815	-1.20561	2.7393
Δ_2HB_{16-04}	-0.01367	-0.01401	1.5600
$_2SPD_{16}$	10.54596	10.48309	1.3276
Constant	-57540.84766	-57436.34766	

TABLE VII. SAN DIEGO WET SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 3 AND 4

SEASON & CATEGORY	FOG PERCENTAGE	NO-FOG PERCENTAGE
DRY (1+2)	78.0	79.3
WET (1+2)	75.4	81.6
DRY (3+4)	85.0	86.1
WET (3+4)	87.0	81.4
WEIGHTED AVERAGE	82.2	81.3

TABLE VIII. SAN DIEGO FOG AND NO-FOG DISCRIMINATION PERCENTAGES

CATEGORY	NUMBER & CLASSIFICATION
1	25 FOGGERS
2	692 NO-FOGGERS
3	7 FOGGERS
4	78 NO-FOGGERS

TABLE IX. OAKLAND DRY SEASON FOG AND NO-FOG CASES

CATEGORY	NUMBER & CLASSIFICATION
1	66 FOGGERS
2	345 NO-FOGGERS
3	123 FOGGERS
4	246 NO-FOGGERS

TABLE X. OAKLAND WET SEASON FOG AND NO-FOG CASES

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
$\Delta_1 RH_{16}$	0.12679	0.06999	6.8501
$\Delta_1 THK_{16}$	-0.00299	-0.00066	9.4800
$_2SPD_{16}$	1.05340	1.28505	4.5235
$\Delta_2 SLP_{04}$	-0.13446	0.01399	3.5524
$\Delta_1 TDB_{04}$	-0.22813	0.06931	3.9888
ΔSI_{04}	(Removed at step 15)		
$\Delta_2 SI_{04-16}$	0.07802	0.22367	4.9993
$\Delta_1 SI_{04}$	(Removed at step 16)		
$_1SI_{04}$	0.59826	0.52878	2.1779
$\Delta_2 DIR_{16}$	0.00227	-0.00105	1.1546
$_2DIR_{04}$	0.04460	0.04094	1.8274
$_3HB_{16}$	0.00316	0.00258	1.6784
$_3SPD_{04}$	0.63973	0.76082	1.9224
$\Delta_2 TI_{04}$	0.08523	-0.07332	5.2857
Constant	-13.89205	-13.44692	

TABLE XI. OAKLAND DRY SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 1 AND 2

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_1RH_{16}$	3.34849	3.27486	10.2524
${}_1TT_{16}$	-3.08567	-3.17853	16.3925
${}_1SLP_{04}$	42.07230	42.00005	5.6511
ΔSI_{04}	-9.95635	-9.84301	5.4529
${}_3DIR_{16}$	-0.17242	-0.16732	6.7092
$\Delta_1 TB_{04-16}$	0.02788	-0.04618	7.7952
$\Delta_2 WET_{16}$	-4.01388	-4.08238	2.8188
$\Delta_2 DIR_{16}$	-0.11382	-0.11060	4.4790
$\Delta_1 TDB_{04}$	(Removed at step 17)		
$\Delta_2 SI_{04-16}$	8.11221	8.20044	2.5340
$\Delta_1 HB_{16}$	-0.00199	-0.00223	2.8280
$\Delta_2 THK_{16}$	-0.09082	-0.09181	2.5174
${}_3DIR_{04}$	0.13206	0.13412	1.9915
${}_1HB_{04}$	0.00785	0.00697	4.7836
$\Delta_1 HB_{04}$	0.02822	0.02869	3.0078
$\Delta_1 DPD_{16-04}$	7.96099	7.82930	2.5799
${}_3THK_{04}$	-0.03665	-0.03714	1.2301
${}_1WET_{04}$	9.87953	9.94415	1.1570
Constant	-21517.31641	-21437.86719	

TABLE XII. OAKLAND WET SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 1 AND 2

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
ΔDPD_{04}	4.41206	8.59220	5.7808
ΔWBD_{04}	-9.61003	-15.05353	2.6278
$_1HT_{16}$	0.00639	0.00851	2.2578
Δ_2DIR_{16}	(Removed at step 12)		
Δ_1SI_{16-04}	-0.19130	0.27583	6.8050
$_2TB_{04}$	-1.24039	-0.81018	2.3739
$_2SI_{16}$	1.40700	0.73658	6.6531
Δ_1SPD_{04-16}	(Removed at step 18)		
$_2FS_{16}$	-0.96936	3.33698	12.4420
$_2TWB_{16}$	7.61710	5.66939	8.4864
Δ_2SLP_{04}	-0.30712	0.30540	2.9913
Δ_2SPD_{04-16}	(Removed at step 21)		
$_1TDB_{16}$	2.40190	3.20982	3.0565
Δ_2TI_{04}	-0.42721	-0.65045	1.7665
$_2SPD_{16}$	1.35426	2.62428	9.8126
$_1TT_{16}$	-1.02120	-0.61391	5.4850
Δ_1TI_{16}	0.44584	-0.16509	2.7886
Δ_2SPD_{04}	-0.04702	-0.60388	3.4339
Constant	-76.13808	-73.33984	

TABLE XIII. OAKLAND DRY SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 3 AND 4

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_1RH_{16}$	22.77654	22.63602	7.2474
${}_1TT_{16}$	-11.35367	-11.43764	11.3471
${}_3SLP_{16}$	2.84706	2.60788	5.6923
ΔSPD_{16}	-5.79911	-5.69068	10.4081
${}_3DIR_{04}$	0.23442	0.23942	6.5569
$\Delta_1 SLP_{04-16}$	31.59393	31.41635	8.6105
${}_1HT_{04}$	-0.01989	-0.01919	9.8690
${}_1DPD_{16}$	64.52661	64.19128	2.6085
${}_3TB_{16}$	-2.40382	-2.48583	8.0632
${}_2TDP_{16}$	(Removed at step 23)		
${}_3THK_{04}$	0.02141	0.02209	3.4260
$\Delta_1 TI_{04-16}$	7.10984	6.99197	2.4149
${}_3FS_{04}$	-7.96592	-8.12432	1.0617
$\Delta_2 TT_{04}$	-4.41379	-4.44339	1.0977
$\Delta_2 SLP_{04}$	-32.83693	-32.94241	2.7667
${}_2FS_{16}$	-103.94606	-104.36403	2.9697
$\Delta_1 FS_{16}$	-57.20595	-57.47128	2.5596
ΔDIR_{04}	0.38270	0.38461	1.6718
$\Delta_2 DIR_{04-16}$	0.21845	0.21671	2.0633
$\Delta_2 DPD_{16}$	-0.53928	-0.87731	2.7606
$\Delta_2 RH_{16}$	-1.36683	-1.42692	1.4863
${}_1TDB_{16}$	21.05357	21.17676	4.4619
${}_1TWB_{04}$	-19.81030	-19.91208	1.7678
${}_2SLP_{04}$	69.76450	69.88263	1.2062
Constant	-38127.37891	-37993.56641	

TABLE XIV. OAKLAND WET SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 3 AND 4

SEASON & CATEGORY	FOG PERCENTAGE	NO-FOG PERCENTAGE
DRY (1+2)	76.0	74.6
WET (1+2)	78.8	73.0
DRY (3+4)	85.7	98.7
WET (3+4)	76.4	81.3
WEIGHTED AVERAGE	77.4	76.8

TABLE XV. OAKLAND FOG AND NO-FOG DISCRIMINATION PERCENTAGES

CATEGORY	NUMBER & CLASSIFICATION
1	47 FOGGERS
2	67 NO-FOGGERS
3	290 FOGGERS
4	270 NO-FOGGERS

TABLE XVI. QUILLAYUTE DRY SEASON FOG AND NO-FOG CASES

CATEGORY	NUMBER & CLASSIFICATION
1	39 FOGGERS
2	91 NO-FOGGERS
3	327 FOGGERS
4	225 NO-FOGGERS

TABLE XVII. QUILLAYUTE WET SEASON FOG AND NO-FOG CASES

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
$\Delta_2 THK_{04}$	(Removed at step 28)		
ΔWET_{16}	(Removed at step 18)		
$\Delta_1 SPD_{16-04}$	-12.59450	-12.84844	3.5198
$\Delta_2 SI_{04}$	(Removed at step 23)		
$_3HT_{04}$	0.02701	0.02604	3.1081
$_3SI_{16}$	23.46292	23.03337	2.9156
$_3HB_{16}$	0.05579	0.05850	5.3234
$\Delta_1 TI_{04}$	-54.50514	-55.63574	29.4205
$_1DIR_{04}$	-2.06415	-2.08957	21.8740
$\Delta_2 RH_{16}$	0.02754	-0.03313	4.8483
$\Delta_1 SPD_{16}$	23.25471	23.53885	5.7243
$\Delta_2 DPD_{04}$	9.75030	10.26355	10.0187
$_2WBD_{04}$	(Removed at step 25)		
$\Delta_1 TB_{04}$	(Removed at step 29)		
$\Delta_2 TI_{04-16}$	-58.78047	-60.06639	23.5783
$_2SLP_{16}$	85.17726	85.38756	6.3899
$\Delta_1 TWB_{16-04}$	-21.78006	-22.06129	1.9874
ΔRH_{16}	-9.34072	-9.59527	16.8019
$\Delta_1 DIR_{04}$	1.33832	1.35184	10.7870
ΔTDP_{16}	27.53899	28.27422	11.6391
$\Delta_1 TI_{16-04}$	-50.82481	-51.49023	7.8411
$\Delta_1 THK_{04}$	-0.20962	-0.21217	4.7505
$\Delta_2 TT_{16-04}$	0.76721	0.85447	2.8860
$_1HB_{04}$	0.13531	0.13775	8.0030
$\Delta_2 HT_{04-16}$	-0.01931	-0.01804	1.7703
$_1DPD_{04}$	-20.46352	-20.74287	1.3205
$_2HB_{16}$	-0.09945	-0.09997	1.0058
Constant	-43064.78516	-43273.94141	

TABLE XVIII. QUILLAYUTE DRY SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 1 AND 2

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_1SPD_{16}$	13.96301	13.56759	27.1404
${}_2SLP_{16}$	18.23346	18.10907	14.1167
Δ_2TDP_{04}	1.03278	0.90201	2.4866
${}_2HB_{16}$	-0.07289	-0.07226	2.3006
${}_1DPD_{16}$	(Removed at step 21)		
${}_2HT_{16}$	(Removed at step 16)		
${}_2DIR_{04}$	0.18567	0.16958	14.3619
${}_1DIR_{16}$	(Removed at step 14)		
Δ_1TI_{04}	-21.14665	-20.92448	3.6018
${}_1THK_{04}$	(Removed at step 19)		
${}_3DIR_{04}$	-0.20689	-0.19983	4.2505
Δ_2DIR_{04-16}	0.10502	0.11072	4.7000
Δ_1THK_{16}	-0.10421	-0.10166	5.5468
Δ_2TT_{16-04}	0.38224	0.25265	6.2855
${}_1SPD_{04}$	-4.36938	-4.17476	4.9473
Δ_2TI_{04-16}	13.52794	13.18516	5.4682
Δ_2SPD_{16-04}	2.10825	2.01247	1.9396
Δ_1TDP_{16-04}	-5.01223	-5.12174	1.3300
Δ_2SI_{16}	-4.28529	-4.10700	1.1963
Constant	-9291.10938	-9163.24219	

TABLE XIX. QUILLAYUTE WET SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 1 AND 2

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_1RH_{16}$	10.36016	10.21278	34.0688
ΔTI_{04}	3.93438	3.88034	2.8793
${}_1TI_{16}$	26.64711	26.28835	12.3250
${}_1WET_{16}$	-21.50443	-21.19310	8.5402
${}_1DIR_{16}$	-0.62858	-0.63444	9.6180
$\Delta_1 DIR_{04}$	0.10819	0.11094	5.5265
$\Delta_2 TT_{04}$	-0.81858	-0.87311	8.3780
$\Delta_2 FS_{16}$	1.16413	1.00654	4.2382
$\Delta_2 TDP_{04-16}$	-6.98908	-6.84136	7.3719
$\Delta_1 THK_{04}$	-0.00598	-0.00620	2.6089
ΔDPD_{04}	0.47370	0.63786	3.9646
${}_1SLP_{16}$	49.51489	49.56006	4.1959
$\Delta_2 SPD_{04-16}$	1.84741	1.80900	2.2311
$\Delta_1 DIR_{16-04}$	0.62066	0.62268	1.5758
ΔHB_{16}	-0.01738	-0.01752	1.9450
$\Delta_2 THK_{16}$	0.02608	0.02658	1.4060
${}_3TWB_{16}$	7.12852	7.20581	3.2643
${}_1TT_{04}$	-0.75415	-0.79099	1.9279
$\Delta_1 TWB_{04-16}$	-0.49160	-0.63447	3.5914
${}_1SPD_{16}$	14.06279	14.09487	1.1353
$\Delta_1 WET_{04}$	-7.78271	-7.70232	1.9297
ΔHB_{04}	0.01489	0.01461	2.7728
${}_1HB_{04}$	-0.01064	-0.01032	1.8722
Constant	-25618.90625	-25653.00781	

TABLE XX. QUILLAYUTE DRY SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 3 AND 4

VARIABLE	Coefficients of the: FOG FUNCTION	NO-FOG FUNCTION	FINAL F VALUE
${}_{1}RH_{16}$	4.04704	3.95495	75.9569
${}_{1}TI_{16}$	-6.03803	-6.21370	19.3615
${}_{3}FS_{16}$	2.93756	2.72885	7.0713
${}_{1}FS_{16}$	(Removed at step 15)		
ΔDIR_{04}	-0.12554	-0.12898	7.6744
$\Delta_{1}HB_{04-16}$	0.01320	0.01337	2.0153
$\Delta_{1}SPD_{16-04}$	-1.65702	-1.71154	7.9495
${}_{1}WBD_{04}$	30.97249	30.44763	10.2992
${}_{1}FS_{04}$	-1.81256	-2.01150	5.9802
${}_{3}THK_{04}$	-0.02820	-0.02772	4.1084
$\Delta_{1}DIR_{16}$	0.20934	0.20692	5.8071
${}_{1}SLP_{04}$	13.66911	13.64324	4.7360
${}_{3}TT_{16}$	1.19262	1.13235	5.8522
${}_{3}TWB_{16}$	0.04358	0.12552	4.2738
$\Delta_{1}DIR_{04}$	0.02501	0.02693	1.9975
ΔHB_{04}	-0.00430	-0.00412	1.9398
$\Delta_{1}RH_{16}$	-2.32839	-2.31851	1.2658
Constant	-7134.03516	-7101.53516	

TABLE XXI. QUILLAYUTE WET SEASON FOG AND NO-FOG CLASSIFICATION FUNCTIONS FOR CATEGORIES 3 AND 4

SEASON & CATEGORY	FOG PERCENTAGE	NO-FOG PERCENTAGE
DRY (1+2)	85.1	82.1
WET (1+2)	84.6	82.4
DRY (3+4)	71.0	75.5
WET (3+4)	75.8	70.7
WEIGHTED AVERAGE	74.9	75.5

TABLE XXII. QUILLAYUTE FOG AND NO-FOG DISCRIMINATION PERCENTAGES

CATEGORY	NUMBER & CLASSIFICATION
1	35 FOGGERS
2	350 NO-FOGGERS
3	20 FOGGERS
4	97 NO-FOGGERS

TABLE XXIII. SAN DIEGO DRY SEASON FOG AND NO-FOG CASES FOR THE TEST DATA SAMPLE

CATEGORY	NUMBER & CLASSIFICATION
1	40 FOGGERS
2	250 NO-FOGGERS
3	76 FOGGERS
4	150 NO-FOGGERS

TABLE XXIV. SAN DIEGO WET SEASON FOG AND NO-FOG CASES FOR THE TEST DATA SAMPLE

SEASON & CATEGORY	FOG PERCENTAGE	NO-FOG PERCENTAGE
DRY (1+2)	51.4	78.6
WET (1+2)	70.0	73.2
DRY (3+4)	50.0	72.2
WET (3+4)	80.3	67.3
WEIGHTED AVERAGE	68.4	74.3

TABLE XXV. SAN DIEGO FOG AND NO-FOG DISCRIMINATION PERCENTAGES FOR THE TEST DATA SAMPLE

APPENDIX A

A GENERALIZED FORTRAN PROGRAM FOR APPLICATION
OF THE CLASSIFICATION FUNCTIONS

```
C       VAR(I) = VARIABLE RAW VALUE
C       N = NUMBER OF TERMS IN THE CLASSIFICATION EQUATION
C       CF(I) = FOG FUNCTION COEFFICIENT
C       CNF(I) = NO-FOG FUNCTION COEFFICIENT
C       DF = FOG DISCRIMINANT SCORE
C       DNF = NO-FOG DISCRIMINANT SCORE
C       PPF = POSTERIOR PROBABILITY OF FOG
C       PPNF = POSTERIOR PROBABILITY OF NO-FOG
        DIMENSION VAR(N),CN(N),CNF(N)
        DF = CONST
        DNG = CONST
C       READ IN THE VARIABLE RAW VALUES
        READ(5,5) (VAR(I),I=1,N)
      5 FORMAT(8F10.2)
C       MULTIPLY THE N VALUES OF THE VARIABLES BY THEIR
C       ASSOCIATED COEFFICIENTS AND SUM
        DO 10 I=1,N
        DF = DF + CF(I)*VAR(I)
        DNF = DNF + CNF(I)*VAR(I)
     10 CONTINUE
```

```
C      TO AVOID TRYING TO EXPONENTIATE A NUMBER TOO LARGE
C      TO BE REPRESENTED BY THE IBM 360 COMPUTER DO THE
C      FOLLOWING:
       DMIN = AMIN1(DF,DNF)
       DIFF = DF - DMIN
       IF(DIFF.GE.-174.67) GO TO 20
       DIFF = 0.0
    20 PF = EXP(DIFF)
       DIFF = DNF - DMIN
       IF(DIFF.GE.-174.67) GO TO 30
       DIFF = 0.0
    30 PNF = EXP(DIFF)
       SP = PF + PNF
C      NOW FORM THE POSTERIOR PROBABILITIES
       PPF = PF/SP
       PPNF = 1.0 - PPF
C      NOW OUTPUT THE PROBABILITIES IN ANY DESIRED FORMAT
       STOP
       END
```

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